Probabilistic Risk Assessment for High-Energy Laser Safety

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> "In this global economy, there is, and should be, increasing efforts to harmonize toxicological testing, clinical trials, and now *risk assessment* on an international basis."
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> The Presidential/Congressional
> Commission on Risk Assessment
> and Risk Management, Final Report, Volume 2, 1997

Abstract

The application of risk assessment to laser applications is achieved in international safety standards through the use of a laser classification system. For the higher risk classes additional control measures are required (e.g. warning signs, interlocks). These are designed to prevent accidental exposure, leading to injury. Additional calculations help to define a hazard area within which an accidental exposure might lead to harm. This simplicity of approach is entirely appropriate for the vast majority of indoor laser applications. However, in the case of the outdoor use of high-energy lasers, where the likelihood of accidental exposure may be small, it leads to the definition of unrealistically large hazard areas. For these systems it is more realistic to use probabilistic techniques to assess the real risks, and to guide the management decision making process.

Introduction

Society is far better informed today about the dangers to it, and the environment, than in the past. We are well aware that the possibility of suffering physical harm is an inevitable consequence of living, and that although new technologies can do much to reduce these risks, they can also create new ones. The introduction of a new technology therefore carries with it a decision that has to be made with respect to the associated risks, and whether these are acceptable.

Quantitative risk analysis techniques are finding increasing applications in supporting decision making about risk, especially for dealing with uncertainties about the likelihood of events such as the failure of a safety critical component, and dose-response curves for toxic hazards. The merit of the numerical approach is that it allows comparisons other than of a purely qualitative kind to be made. For environmental protection in the US there is a growing interest in the use of analytic tools to improve the regulatory process. Indeed, the Environmental Protection Agency have recently announced (1)

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that risk-based assessment will be the basis for the future evaluation of environmental hazards to health, with probabilistic techniques playing a key role in characterizing variability and uncertainty.

International standards for laser safety (2,3) have embraced risk analysis in their development, both in the derivation of maximum permissible exposure (MPE) levels, and in the development of hazard classes (4). However, the traditional approach to laser protection, embodied in these standards, is that of a deterministic hazard assessment. This involves the calculation of the MPE for the laser system under consideration, and a determination of an area within which an exposure could potentially exceed this level. Safety is guaranteed by excluding persons from this area.

Whilst this technique is effective for normal applications, for situations where the likelihood of human exposure within this area is small, it leads to unreasonably large hazard zones. In these cases it is more appropriate to embrace probabilistic risk assessment techniques to augment the hazard assessment and support risk management decisions.

Terminology and Definitions

With most disciplines, terminology and definitions can vary widely, and risk analysis and management is no exception. It is therefore appropriate to lay down some important definitions at the start. These definitions are taken from the International Standards Organization (ISO) Guide 51 (5), which is published by ISO to advise the authors of ISO standards on how to include safety aspects.

- **harm -** physical injury or damage to the health of people or damage to property or the environment
- **hazard** - potential source of harm
- **harmful event** - occurrence in which a hazardous situation results in harm
- **risk** - combination of the probability of occurrence of a harmful event and the severity of that harm
- **tolerable risk** - risk which is accepted in a given context based on the current values of society
- **residual risk** - risk remaining after protective measures have been taken
- **safety** - freedom from unacceptable risk

Risk is clearly a combination of two factors - the probability that an adverse event will occur (such as a specific disease or type of injury) and the consequences of the adverse event (severity of harm). Any definition of risk must encapsulate both these factors.

Interestingly, and somewhat aside, the ISO guide also states explicitly that the use of the word *safety* and *safe* as descriptive adjectives “should be avoided” because they “convey no extra useful information”. In addition, they are likely to be interpreted as an assurance of guaranteed freedom from risk. Their recommended approach is to replace, wherever possible the words safety and safe by an indication of the objective, e.g. *protective helmet* instead of *safety helmet*, *emergency switch* in lieu of *safety-switch*.

The Risk Management Process

Risk management is the process of identifying, evaluating, selecting, and implementing actions to reduce risk to human health to a level that is regarded as acceptable. The goal of risk management is scientifically sound, cost-effective, integrated actions that reduce or prevent risks while taking into account social, cultural, ethical, political, and legal considerations.

A good risk management decision is one that addresses a clearly articulated problem in its public health and ecological context (6). It emerges from a decision-making process that elicits the views of those affected by the decision, so that differing technical assessments, public values, knowledge, and perceptions are considered. It is based on a careful analysis of the weight of scientific evidence that supports conclusions about a problem's potential risks to human health and the environment, and is made after examining a range of regulatory and non-regulatory risk management options.

In its final report, the US Presidential The Presidential/Congressional Commission on Risk Assessment and Risk Management (7) provides a risk management framework with six key stages (Figure 1):

- Define the problem and put it in context.
- Analyze the risks associated with the problem in context
- Examine options for addressing the risks
- Make decisions about which options to implement
- Take actions to implement the decisions
- Conduct an evaluation of the action's results

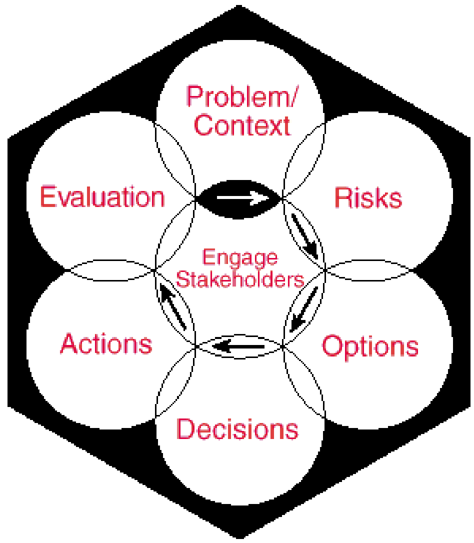

Figure 1. Risk management framework

In the context of this framework, the goal of probabilistic risk assessment in laser safety is to support the first three of these stages – to formulate the problem, analyze the risks, and examine options for addressing the risks. Assessing these risks entails the use of scientific data, assumptions and mathematical models to estimate the likelihood, frequency, and severity of harm to people exposed to the hazard.

Deterministic Laser Safety

Laser beams are characterized by their extremely small beam divergence (typically less than 1 mrad), which means that the potentially hazardous radiant power or energy in the beam can be propagated over long distances. Because the beam irradiance (or radiant exposure) ultimately[1] decreases as a function of the distance from the laser source, the beam divergence will ultimately limit the range at which the laser is hazardous. International standards (2, 3) use this phenomenon, and the maximum permissible exposure to evaluate the hazard from laser systems.

The distance along the axis of the beam from the laser beyond which the irradiance (or radiant exposure) is not expected to exceed the MPE is defined as the nominal ocular hazard distance (NOHD). Similar definitions may be used for the evaluation of skin hazards. By allowing for all the possible pointing directions of the beam, and scattered and reflected radiation, a nominal hazard zone can be described. This is the space within which the direct, scattered, or reflected radiation during operation exceeds the MPE. Safety is guaranteed by excluding persons from this area.

The deterministic assessment therefore analyses the potential hazards associated with the use of the laser system in a particular scenario, and then tacitly assumes that the

[1] for some laser systems the laser beam may be initially convergent

hazards will be realized. Whilst this treatment is not unduly restrictive for normal applications, for situations where the likelihood of human exposure within this area is small, e.g. an airborne laser range-finder, it can lead to unrealistically large hazard zones (Figure 2). One of the main problems is that it evaluates the risks as if the laser points in all possible directions simultaneously and then eliminates the hazard by vacating this area.

In these cases it is more appropriate to embrace probabilistic risk assessment techniques to augment the hazard assessment and provide risk-based management decisions. The intention is not for probabilistic analyses to replace the conventional approach, but for the technique to be available as “second-tier”, advanced methodology. This is then applied in situations where the likelihood of ocular exposure is clearly small, and, through the deterministic analysis, this leads to disproportionate restrictions on the laser use.

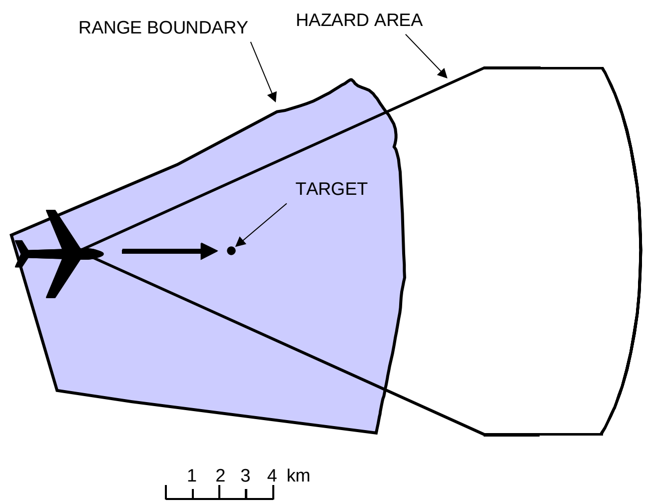

Figure 2. Schematic laser hazard area trace for a laser range finder

Probabilistic Laser Safety Scenario

A probabilistic laser safety scenario can be described as one in which the chance of ocular irradiation is small, and the major elements under consideration are inherently probabilistic. The probabilistic assessment seek to deal with the uncertainties associated with the hazard assessment by asking the following questions:

- Is there somebody at that location?
- Does the laser irradiate them?
- If they are irradiated, what is the exposure level?
- Is this exposure level sufficient to cause harm?

These uncertainties are usually represented by probability distributions, which describe the likelihood that a quantity will take on a given value within a range of all possible levels.

The author has previously described the fundamentals of probabilistic laser safety (8,9), and so only a brief account of the main principles is given here. For a representative outdoor laser application in the military environment, typical probabilistic elements would be:

- population models for the area under consideration
- laser aiming and tracking performance
- equipment performance and failure parameters
- atmospheric propagation models
- ocular damage models (dose-response curve)

The probabilistic model is obtained by defining probability density functions for all of the elements which might lead to a risk of ocular damage, multiplying all of these functions together, and integrating over all relevant ranges of associated parameters. The number and nature of probabilistic distributions is assessed on a case by case basis, and will depend on the degree of complexity to be applied. However, the basic framework remains the same in that there is always an element which defines the overall expectation, E_{OD}, of a population of unwarned or unprotected persons sustaining a certain minimum level of ocular damage should not exceed a maximum acceptable level. The expectation can be derived from an equation of the general form:

$$E_{OD}(X) = P_I(X)\int_0^{\infty} P_S(g_s)P_{OD}(g_s H(X))dg_s$$

$$\begin{aligned}
&\text{where :}\\
X &= \text{any general point on land, sea, or air}\\
P_I(X) &= \text{the probability that someone is located at } X\\
H(X) &= \text{nominal radiant exposure at the point } X\\
P_{OD}(g_s H(X)) &= \text{probability of ocular damage if exposed to } g_s H\\
g_s &= \text{gain in exposure due to atmospheric effects}\\
P_S(g_s) &= \text{probability density function for } g_s
\end{aligned}$$

For high-energy laser systems there is also likely to be a significant risk from reflected radiation. The nature of the reflecting surface (shape, reflectivity, orientation) will determine the characteristics of the reflected beam, and these may require additional probabilistic elements in the assessment.

Damage Criterion - the Ocular Damage Model

The ocular damage model is one of the most important elements in the risk assessment. It describes the likelihood that a given level of exposure will cause a given level of damage. The form of the distribution will be dependent on the level of harm under consideration. It has been recommended (10) that the level should be small but easily detectable, and the consequent visual impairment should be small, but not insignificant. The minimal visible lesion level, defined as minimum observable level of retinal damage detectable by direct ophthalmic investigation, which has been used extensively in laser bioeffects studies, is consistent with these criteria.

An important consideration in risk management is the severity of the harm (Table 1), and it is useful to consider the minimum visible lesion in this context.

SEVERITY	Catastrophic	Death or permanent total disability, system loss, major property damage.
	Critical	Permanent partial disability, temporary total disabilities in excess of 3 months, major system damage, significant property damage.
	Marginal	Minor injury, lost workday accident, compensable injury/illness, minor system/property damage.
	Negligible	First aid or minor supportive medical treatment, minor system impairment.

Table 1. Levels of severity of harm for risk analysis

The extent of visual losses from a retinal lesion will depend on both the size of the retinal injury and it's proximity to the fovea, a specialized region of the retina that is responsible for seeing fine detail. A small lesion outside the fovea may not disturb vision significantly (11), and visual function would be compromised minimally, unless the central foveola was involved, and even then some recovery might be expected (12). The severity of harm from a minimum visible lesion would therefore be considered to be negligible for lesions in the parafovea, marginal in the fovea, and potentially critical in the foveola.

Acceptable Risk Level

Tolerable risk results from the balance between the ideal of absolute safety and the demands to be met by the new technology, both individual and societal, suitability for purpose, cost effectiveness, and the conventions of the society concerned (Figure 3). The iterative process of risk assessment (risk analysis and risk evaluation), and risk reduction is used to achieve tolerable risk.

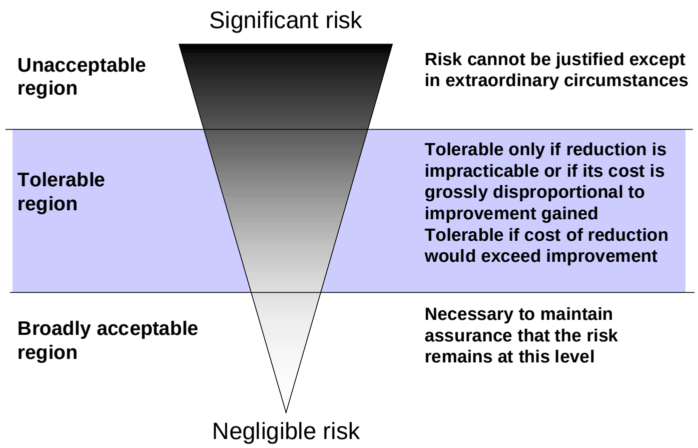

Figure 3. The concept of tolerable risk

The UK MOD, which has used quantitative risk assesment as a tool to manage the risks associated with the airborne use of laser range finders, have used a risk level of 1 in 10^8 for each laser firing (8). Although the numerical value is extremely low, it is useful in that it serves to illustrate that laser risk is minimal. This level was decided on the basis of the expected total number of laser firings per year (ca. 10^3) to give an annual risk which compares favourably with the risk from other activities (Table 2).

FATAL RISK (per annum)	*LEVEL*
from five hours of solo climbing every weekend	1 in 100
due to working in relatively high risk groups (e.g. mining)	1 in 1,000
General risk of death in a traffic accident	1 in 10,000
in an accident at work in the very safest part of industry	1 in 10,000
on the ground in the US by a crashing airplane (lifetime risk)	1 in 200,000
General risk from fire or an explosion from gas at home	1 in 1,000,000
by lightning	1 in 10,000,000

Table 2. Levels of fatal risk (average figures, approximated) per annum

Summary

Health and safety legislation in general places a duty of care on employers in respect of their employees and other persons affected by work activities, and the requirement to provide a safe place of work. The implementation of probabilistic techniques in laser safety can be cited as a rigourous example of exercising this 'duty of care'. The application can also be regarded as consistent with the assessments of the risk from other hazards, such as explosion, blast and toxic risk, many of which are particularly pertinent to military scenarios.

It would be unreasonable to suggest the use of a formal probabilistic approach for all laser safety assessments. If the deterministic approach does not give rise to unreasonable restrictions on the laser use then it is much simpler to adopt this approach. However, where it would restrict the use of the laser system unnecessarily, then a probabilistic risk assessment can be used to augment the conventional approach, and evaluate the real risk to human health from the laser system.

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